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Attitude Maintenance Using an Off-Boresight Helmet-Mounted Virtual Display

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SUMMARY

Helmet-mounted displays (HMDs) enable flight information to be displayed within the pilot's field-of-view, regardless of head position in the cockpit. The present research initiates the investigation of an off-boresight HMD (OBHMD), which appears when the pilot's head position is greater than 20-degrees from the aircraft's boresight. Nine subjects flew a simulated, low-level, high-speed, airborne surveillance/ reconnaissance mission, while monitoring a hostile adversary aircraft. The results indicate pilots were able to spend more time and look further off-boresight with an OBHMD than without one. In addition, missions with an OBHMD produced fewer terrain impacts. This research effort has demonstrated the promising performance benefits an OBHMD affords, as well as the need for further research to optimize OBHMD symbology.

1 INTRODUCTION

Throughout the history of avionics development, researchers have been concerned with moving flight information closer to the aviator. In this case, "closer" refers to both physical closeness and perceptual or cognitive proximity. As with the automobile, flight instruments have traditionally been on a panel in front of the pilot or operator. This configuration required the pilot to look inside the cockpit to receive necessary flight information. In the late 1950s, as aircraft became faster, and weapon systems more sophisticated, the flight environment became less forgiving of the time taken to look into the cockpit. In response to these demands, the head-up display (HUD) was developed, effectively moving flight information closer to the pilot.

The HUD optically presents a virtual image containing flight and status information, reflecting it from a transparent combiner glass to the pilot. The HUD is fixed to the top of the aircraft instrument panel so that the pilot can look through the display and windscreen in order to view the outside world. Theoretically, the pilot need only shift attention between the HUD information and natural out-the-window cues to be aware of both his surroundings and the aircraft status (situation awareness). The HUD significantly reduces the need for the pilot to look down into the cockpit, thus minimizing the associated risks of failing to see an airborne or ground threat. The HUD also enables unique information, such as the flight path marker (FPM), to be displayed. The FPM symbology displays the aircraft's automatically computed instantaneous velocity vector, irrespective of actual attitude or angle-of-attack. Essentially, the FPM represents the line or "wire" along which the aircraft is traveling, and the impact point if the aircraft were to continue on its present course. Traditional instrumentation required the pilot to scan, interpret, and integrate information from several instruments to determine the flight path.

Over the past several decades, aircraft mission environments have required pilots to fly ever faster, at lower and lower altitudes, with ever increasing sensor technology and weapon system capabilities. Under some conditions, it is now dangerous for the pilot to view anything other than the outside world and critical flight information superimposed upon it. Whereas HUDs limit information display to the forward field-of-view, helmet-mounted displays (HMD's) provide vital information within the pilot's field-of-view regardless of head position within the cockpit. The HMD is coupled to the head via a three-space tracker which monitors the helmet's position within a coordinate system of three orthogonal (x, y, and z) planes and updates the display symbology or sensor position accordingly. According to Furness (1986), graphics or symbols presented on the display may be stabilized one of four ways in virtual space: 1) head stabilized: an aim-sight reticle and cockpit-stabilized switches; 2) cockpit stabilized: cockpit displays; 3) earth stabilized: navigation waypoints and surface target locations; and 4) space stabilized: other aircraft and in-flight missiles.

Much like the HUD extended the flight envelope in modern tactical aircraft, the HMD enables the pilot to perform missions that are inherently dangerous or impossible without it. The benefits afforded by the HMD are somewhat intuitive. The HMD permits continuous display of critical flight information within the field-of-view, so that heightened situation awareness may be maintained independent of viewing area or head position. In addition, the HMD enables the use of egocentric or pilot-centered threat radar, such that symbols represent airborne or ground points of interest oriented in their actual position relative to the pilot. The pilot can then perceive and acquire beyond visual range targets in their natural orientation. With a head-coupled light-intensifying or infrared sensor, the HMD can display night vision imagery corresponding to where the pilot is looking. This, plus terrain-profiling command flight-path symbology, should

allow heightened night-flight situation awareness at lower altitudes and higher speeds than can safely be used with present HUD-only forward-looking night vision.

The basic components of HMD instrument flight symbology should indicate heading and aircraft attitude, as well as airspeed, altitude and a head-aiming reticle. The costs and benefits associated with head-coupled flight symbology are presently unknown. It is the responsibility of the HMD scientific community to evaluate the most efficient and effective ways to provide mission relevant information. Intelligent selection among candidate HMD applications must be based on empirically-derived principles of human performance, perception, and cognition. The present research initiates the investigation of a potential off-boresight display for presenting essential flight information for use in tactical mission environments.

2 METHOD

2.1 Subjects

Nine male volunteer current private pilot subjects participated in the experiment. All subjects were between the ages of 25 and 41, with a mean age of 31. All nine subjects were right-hand-dominant and had corrected or uncorrected visual acuity of 20/20 or better. Subjects' overall mean flight time was 532.22 hours, and seven out of the nine pilots were instrument-rated. The subjects did not have any military flight experience. They were paid $5.00 per hour for their participation.

2.2 Apparatus and Stimuli

The simulated visual events were displayed via a large field-of-view head-coupled binocular HMD system. This system consisted of two miniature CRTs and their associated display electronics, graphics generators, and optics, resulting in a field-of-view of 120-degrees horizontal by 60-degrees vertical, with a 40-degree subtended visual angle overlap. The CRT phosphor image was projected by an objective lens as a real image which, viewed through the eyepiece, was displayed as a virtual collimated image. The position of the helmet was measured in six axes with an electromagnetic helmet-position tracker so that the computer-generated images were cockpit, helmet, space, and world stabilized, and were constantly updated. The head tracker system was accurate to within 0.50 degrees, and maintained resolution to within 0.10 degrees.

Subjects were seated in a full-scale F-15 cockpit mock-up, and made control inputs on a center-mounted dynamic joy-stick, side-mounted F-15 throttles, and conventional rudder pedals. The simulated aircraft responded with a generic F-15 aerodynamic model. Figure 1 is a graphical representation of the HMD/simulator system. A Digital Equipment Corporation (DEC) Vax 11/785 computer collected real-time data at a rate of 10Hz.

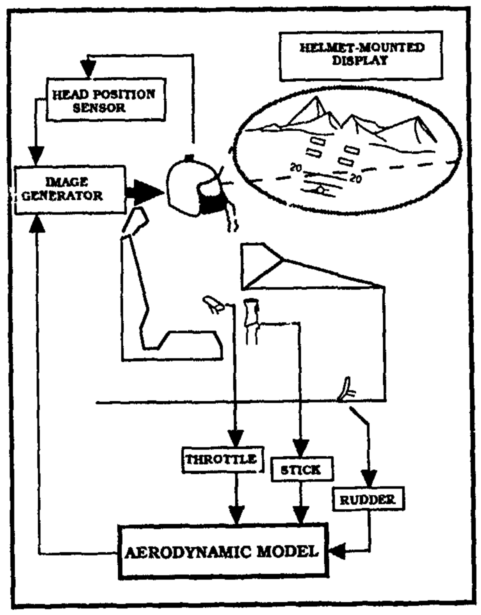

Figure 1. The Visually-Coupled Airborne Systems Simulator diagram.

Subjects flew the simulator through a virtual (world stabilized) terrain gaming area while seated in a computer-generated virtual (cockpit stabilized) cockpit presented by the HMD and generated by Silicon Graphics Iris 3130 raster graphics systems. An Evans and Sutherland stroke-generated line graphic HUD image was superimposed on the raster image and was cockpit stabilized. The HUD represented a slightly modified F-16 block 40 version symbology, and subtended 30 by 30 degrees of visual angle. The off-boresight HMD (OBHMD) symbology was also drawn in stroke graphics and appeared whenever the subject's head position exceeded 20 degrees off the aircraft's boresight. The OBHMD (see figure 2) was helmet stabilized and subtended 25 by 25 degrees of visual angle. The OBHMD symbology represents an aim-sight reticle, aircraft heading scale, digital airspeed, vertical velocity scale (in feet per second), digital/scaled altitude, and an attitude reference indicator (the attitude bars each represent +/-2.5 degrees deflection), with flight path symbol oriented to the aircraft's boresight (longitudinal axis).

2.3 Procedure

Upon entering the research facility, subjects read and signed a standard Air Force consent form. Then they were asked to read a written instruction set designed to familiarize them with the HUD symbology, HMD symbology, task scenario, and basic experimental procedure. Subjects were permitted to ask questions at any point during the instruction set, as well as during the practice and data collection sessions. Each subject participated in three sessions performed over two days. The first two sessions

were used for training (on Day one), while the third session was used for data collection (on Day two). Subjects returned to the laboratory one to eight (an average of four) days later for the data collection session.

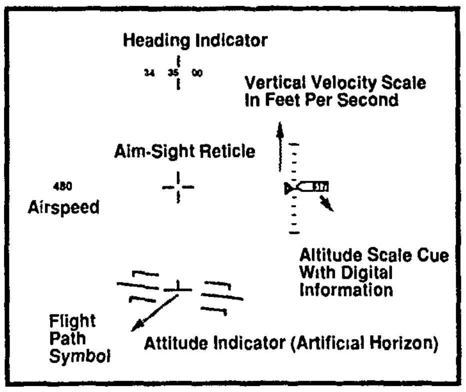

Figure 2. Labeled OBHMD symbology.

2.3.1 Training: The first t aining session was a "free flight" task where subjects flew the simulated aircraft through a threat-free gaming area to become familiar with the aerodynamics model, displays, and helmet apparatus. When adequate ability to maneuver the simulated aircraft was demonstrated (20-30 minutes) and an understanding of the HUD/HMD symbology was indicated, the subject moved on to the second training session. The second training session was a set of trials identical to those from the data collection session, with the exception that subjects were able to review their flight path time histories. The experimenter monitored the subject's progress and acted as an instructor throughout the training sessions. Subjects had a five minute rest halfway through the second training session.

2.3.2 Experimental Task Scenario: The task was a simulated, low-level, high-speed, airborne surveillance/reconnaissance mission. In half of the trials, subjects had a simulated HUD and OBHMD, and in the other half of trials they had only a HUD. Each trial comprised a preview mode, rest mode, run mode, and review mode (review mode for training sessions only). Subjects self-initiated each of the trials and subsequent modes within the trials by pressing the control stick trigger.

Before the start of each trial, the subject was given an overview of the terrain, heading indication and target group via a computer-generated map representing the gaming area. This was called the trial preview mode. When the mission was memorized, subjects selected trial rest mode.

In rest mode, subjects were given a reminder of the mission parameters while the proper heading, altitude and airspeed for the mission ingress was displayed. When aircraft control was activated (the control stick trigger was pulled), subjects were to proceed along a prescribed flight-path (cardinal heading) at an indicated airspeed of approximately 480 knots. Altitude was to be maintained at 400 feet above mean sea level, with terrain threats below 300 feet and surface-to-air missiles tracking above 500 feet. Although subjects were told to fly at 400 feet, there were no adverse consequences for flying below 300 feet, unless altitude went to zero (ending the trial with a terrain impact). However, if the aircraft spent more than seven consecutive seconds above 500 feet, the surface-to-air missiles (SAMs) had sufficient time to lock and fire, terminating the trial.

During trial run mode, subjects flew the simulated aircraft over the gaming area toward a group of targets in the center of the gaming area. Subjects were to continually search for visual contact with an enemy aircraft in the area. The simulated adversary aircraft (bogey) appeared between ownship's 4 and 8 o'clock position. For each trial, the bogey appeared randomly between 5 and 60 seconds after trial initiation, and continued to follow ownship for the remainder of the trial (Figure 3). The bogey randomly moved between ownship's 4, 6, and 8 o'clock position (120, 180, and -120 degrees off-boresight, respectively). When a bogey was visually acquired, the pilot was to fly his present general heading while maintaining as much visual contact with the adversary aircraft as possible (tracking task). Maintaining visual contact with the bogey required the subject to look off-boresight in excess of +/- 90 degrees. On half of the trials the bogey was programmed to fire an air-to-air (AA) missile at ownship from ownship's 4 or 8 o'clock position (hostile bogey condition). A hostile bogey fired a missile randomly between 5 and 75 seconds after the bogey appeared (Figure 3). If the subject neglected to respond to the missile, by ejecting flares and chaff, the trial was terminated. If the subject pressed the flare/chaff button while the missile was in flight, the missile was destroyed and the subject was to abort that mission and initiate a defensive 5.0 g 180 degree turn to egress. The trial would automatically end 30 seconds after the flare/chaff button was pressed. Data collection for that particular trial was terminated when ownship was struck by the missile or the flare/chaff button was pressed. The turn was intended to keep subjects motivated. For non-hostile bogey trials, the adversary would continue to trail the subject's ownship all the way to the target area. Once ownship passed over the target area, the subject was to initiate a 5.0 g 180 degree turn to egress. Trial data collection was terminated when ownship crossed over an imaginary boundary surrounding the target area. Again, the turn was intended to give the subject a difficult task to look forward to during the trial. If the subject missed the target area on the first pass, he was to turn back to the target area and attempt a second pass. On the few occasions that this situation occurred (12 trials), the subject barely missed the 4000 foot

target area diameter, so data collection ended as if no miss occurred (160 seconds after the trial initiation). One hundred and sixty seconds was determined to be an adequate time for ownship to cross over the target area boundary. The trial automatically ended 30 seconds after the target area boundary was crossed. At the end of a trial, subjects were told the cause of trial termination. For the training session only, trial run mode was followed by a trial review mode in which the pilot was able to review his flight path and the adversary's flight path relative to the gaming area. Prior to the data collection session, subjects were given four practice trials. Halfway through the data collection session, subjects were given a five-minute rest.

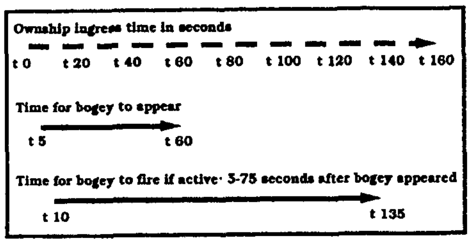

Figure 3. Bogey event time envelopes

X 4 X 2 X 9 within-subjects design. Trials were randomly presented within blocks of the 16 unique conditions formed by crossing the independent variables.

Several dependent measures were recorded and analyzed. These included altitude deviation, percent time spent off-boresight, root mean squared error (RMS) in azimuth for angular helmet position off-boresight, duration and number of exits from the altitude envelope (300 ft. and 500 ft.), reaction time to an AA missile launch, and trial terminator type (successful completion of mission, successful defense of AA missile, ground strike, AA missile strike, or SAM strike). Each trial was divided into two separate phases: the search task, before the bogey was presented (pre-bogey); and the tracking task, after the bogey was presented (post-bogey). Analyses were performed separately for each phase. Reaction time to AA missile launch and trial terminator type-dependent measures, excluding ground and SAM strikes, were unique to the post-bogey data set. In addition, for the post-bogey trial phase only, the absolute angular difference between the bogey and the subject's helmet position at the instant of an AA missile launch was recorded and analyzed.

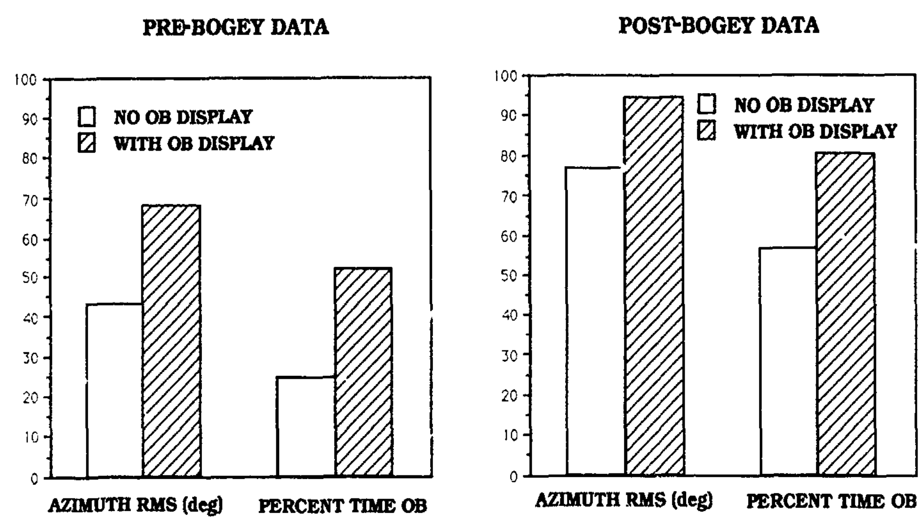

Figure 4. Pre- and post-bogey display main effects for RMS azimuth and percent time off-boresight.

2.4 Design

There were three fully-crossed independent variables included in the within-subjects design: display condition (with or without OBHMD), bogey hostility (bogey would or would not launch an AA missile), and ingress heading (north, east, south, or west). A data collection session contained 32 trials formed by crossing all levels of display condition, bogey hostility, and ingress heading, plus one replication. Two-hundred and eighty-eight total observations were collected for the 2 X 2

3 RESULTS

3.1 Pre-Bogey Phase

A full-factorial within-subjects analysis of variance (ANOVA) was performed for RMS azimuth, percent time off-boresight, and RMS altitude deviation using Display, Bogey Hostility, Heading, and Replication as main effects. The main effect of Display was significant for RMS azimuth ($F = 75.53$, $p < .0001$) and for percent time off-boresight ($F = 50.76$, $p < .0001$), accounting for 26.7 and 31.0% of the variance, respectively. (Statistical

pre-bogey data are less than those for the post-bogey data. This may be due to the subjects moving from the 4 to 8 o'clock position, and back again, more frequently. Another interesting effect was Bogey Hostility. In the post-bogey phase, a non-hostile bogey produced a smaller RMS azimuth, less percent time off-boresight, and more altitude deviation. These effects appear to be attributable to the length of the trial. That is, trial length was longer when the bogey was non-hostile, thus altitude deviations had more time to accumulate. The lack of this effect in the pre-bogey phase lends support to this interpretation.

believed that this is sufficient time for the subject to look away from the bogey (check the HUD or look for the target area) and look back at the bogey in time to see the missile in flight. On the other hand, it was possible that the subject could have, after looking forward, returned his head to the last known location of the bogey, but by that time the bogey had crossed behind to a new position. This would render him vulnerable to a missile strike. This same scenario could be applied to the trials with the OBHMD. When the subject looked on-boresight to check ownship forward progress, he might

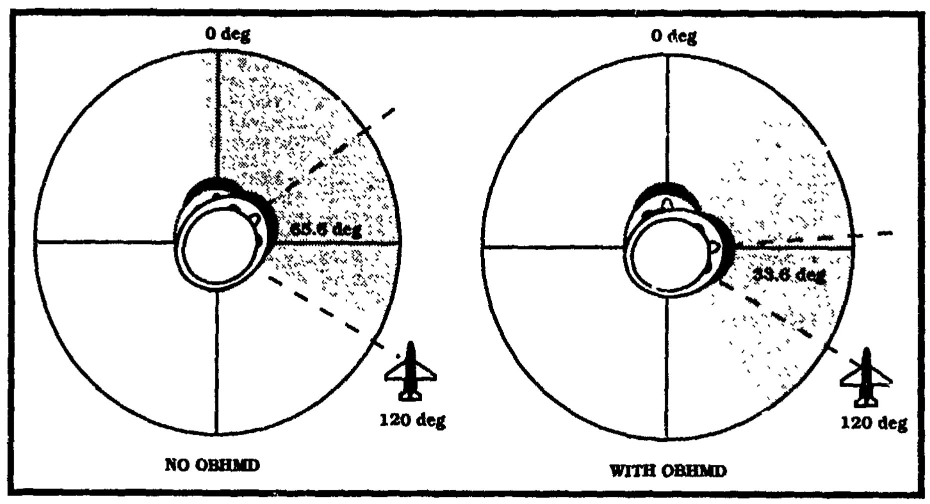

Figure 5. Head azimuth relative to the bogey at instant of AA missile launch.

An OBHMD does not affect the reaction time to deliver flares when defending against a hostile bogey AA missile launch. However, the ABSDAZ indicates that a reaction time difference should indeed be evident. Figure 5 suggests that the subjects were more likely to be looking at the bogey when it launched if they had the aid of the OBHMD. It is possible that, since the subject saw the bogey fire, there was no sense of urgency to press the chaff button. If the subject witnessed the launch, he had a good idea of how long the flight time of the missile would be, and that there was no immediate danger. Exercising this state of relaxation, the subject did not react to the missile with great speed. Without the OBHMD, the subject spotted the missile in flight and, because he did not see the launch, it was imperative to react as fast as possible. If the subject did not see the missile, he may not have had a good feel for the missile time of flight, thus it was urgent that he react to the missile as soon as possible.

The fact that there were no differences between the displays, in terms of number of times hit by an AA missile, may be directly attributable to the flight time of the missile. For the present experiment, the average flight time of the missile from launch to the time it hit ownship was about six seconds. It is not have been able to get to the correct location in time to see the missile in flight. In this case it was a matter of looking at the wrong place at the wrong time.

The findings of the present study suggest that the off-boresight attitude display enhanced the pilot's search capability, tracking performance and survivability. With this display, both the duration of off-boresight visual scanning and the angle with which the pilot was able to scan the aerial environment for bogey aircraft was increased. In addition, the number of times ownship experienced a ground strike with the off-boresight display was zero.

The findings of the present study favor the use of an OBHMD but future efforts should be made to increase the realism of the task. The authors recommend future incorporation of a variable-terrain-elevation gaming area in which the pilots would be required to maintain a constant separation from the surface. Additionally, the expansion of the bogey aerodynamic model to include elevation deviation would permit a much more difficult task and greater element of surprise. It is also reasonable to surmise that although off-boresight attitude display symbology enhanced mission success, the symbol set has yet to be optimized.

5 ACKNOWLEDGEMENTS

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